LOW HUMIDITY AND DAMAGE TO TRACHEAL MUCOSA

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DESPITE the introduction of so many new breathing circuits, valves and canisters for use as anesthesia ventilating equipment, very little attention has been paid to patients' requirements for humidity. Either too little or too much humidity will affect them adversely. Too little humidity will cause loss of mucociliary activity,[1] drying of mucous membrane,[2,3] decreased static compliance,[4] and accelerated body cooling.[5] Too much humidity will cause water intoxication[6] and hyperpyrexia in stress environment.[7] Anesthetic gases are supplied in anhydrous form to prevent clogging of regulators and other valves and, therefore, actually reduce the supply of moisture to the patient. Inhaled gases reach the pulmonary alveoli at body temperature saturated with water vapor.[8] If the gases which enter the tracheobronchial tree are only partly humidified, the trachea and larger bronchi will incur a water debt proportional to the degree of unsaturation of these gases.[9]

CYTOLOGY

To assess the lowest safe degree of humidification during anesthesia we have studied tracheobronchial ciliated epithelial cells which not only cease from playing an active role in the transport of mucus in dry environments but also suffer morphologic changes which can be quantitated by a point scoring system.[3] Eighteen patients undergoing general endotracheal anesthesia were divided into three equal groups. The first group inhaled dry anesthetic gases through a nonrebreathing system, the second group breathed gases with 60% relative humidity at room temperature (22° to 26°C.), controlled by the method of Loew et al.,[10] and the third group breathed gases fully humidified by the method of Weeks and Broman.[11] Tracheobronchial washings were obtained immediately after intubation and at hourly intervals thereafter by instilling 5 ml. of physiologic saline solution down the tracheal tube and suctioning for return one minute after

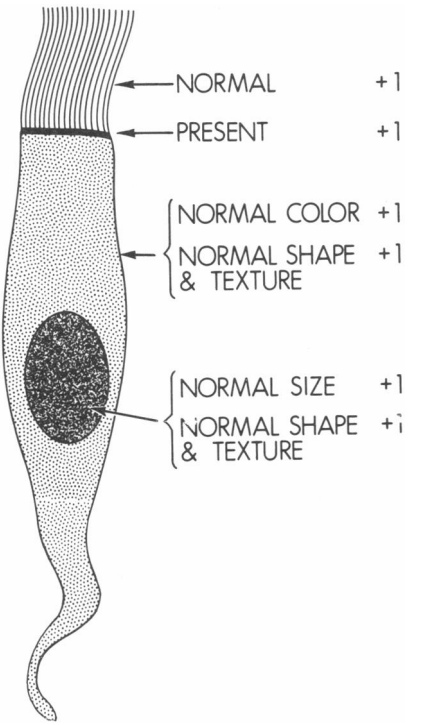

Fig. 1. Scoring system for the assessment of cellular damage. Reproduced by permission from Chalon, J., Loew, D. A. Y., and Malebranche, J.: Effects of dry anesthetics on tracheobronchial ciliated epithelium. *Anesthesiology 37:*338-43, 1972, Figure 1.

instillation. The transparent suction catheter was cut where it was observed to contain secretions retrieved under the pressure exerted by an Ambu bag, spread on glass slides, spray fixed at once, stained by the Papanicolaou method, and examined microscopically. The morphologic integrity of ciliated cells in each specimen was assessed by the point scoring system depicted in Figure 1. One point was assigned for each of the following factors: presence of normal cilia, presence of endplate (ciliomotor apparatus), normal cytoplasmic color (blue), normal cytomorphology, normal nuclear size, and normal nuclear shape and texture. Each cell could score six points. Because 200 cells were examined in each specimen, the total score for each smear could vary from 0 to 1,200. The mean score for all specimens collected at each time interval after exposure in each group are shown in the table. Specimens from patients who breathed partly and fully humidified gases did not show significant cellular changes. Among pa-

TOTAL CELLULAR SCORES OF TRACHEOBRONCHIAL WASHINGS FROM PATIENTS BREATHING DRY GASES, GASES 60% HUMIDIFIED AT ROOM TEMPERATURE, AND GASES FULLY HUMIDIFIED AT 37°C., AT THE ONSET OF ANESTHESIA AND AT HOURLY INTERVALS THEREAFTER.

	N	$\bar{X}$	*SD*	*P*
Dry gases	6			
At once		1,043	90	—
1 hour		920	152	NS
2 hours		751	195	<0.01
3 hours		579	239	<0.01
60% humidity				
22 to 26 C°	6			
At once		1,070	90	—
1 hour		973	161	NS
2 hours		944	150	NS
3 hours		925	163	NS
Saturated humidity,				
37°C.	6			
At once		1,112	33	—
1 hour		1,097	70	NS
2 hours		1,073	91	NS
3 hours		1,103	71	NS

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tients exposed to dry gases, the total score decreased from a control of 1,043 to 920 after one hour, to 751 ($P < 0.01$) after two hours, and to 579 ($P < 0.01$) after three hours. We conclude that gases delivered to patients under general endotracheal anesthesia longer than one hour should have a minimum relative humidity of 60% at room temperature (12 mg. H_2O absolute humidity) to avoid damaging the ciliated cells of the tracheobronchial tree and to protect the effectiveness of the mucociliary transport system.

INSTRUMENTATION

This effort reviewed the humidity output of existing anesthesia systems, studied variations in inhaled moisture resulting from changes in fresh gas inflow, respiratory minute volume and metabolic production of carbon dioxide, and assessed these in relation to safety standards derived from our cytologic studies. In addition, we shall describe two new circuits designed to improve the humidification of inhaled gases.

Role of the ventilator in humidity control. Ventilators placed on circle-absorber systems are exposed to warm overhumidified gases and in time accumulate water of condensation; they play an active role both as humidity regulators and, when wet, as humifiers. Increasing the rate and tidal volumes of these instruments raises the humidity of inhaled gases.[12] A ventilator actively used in a circle absorber system can collect up to 10 g. of water of condensation. If it is transferred to a dry, nonrebreathing system, it will generate an original humidity of 20% at room temperature (22° to 26°C.), which will decrease exponentially to 4% over a six-hour period. Ventilators attached to nonrebreathing or highflow semiclosed tube-bag systems can actively influence inspired humidity only if they are placed at the patient end of humidity generators incorporated into these systems or if they contain water of condensation.

Role of system design in humidity regulation. Humidity in anesthetic circuitry comes from three main sources: from the patient himself because the water vapor he exhales condenses in the mechanical dead space of the system and supplies moisture to inhaled gases, a phenomenon which is accentuated when heat and moisture exchangers are inserted into the circuit; from the reaction of neutralization of soda lime by CO_2, which liberates 28 Kcal. for each mole of CO_2 absorbed; and from water intentionally incorporated into the lime granules by the manufacturer[13] or added into the system by the anesthesiologist.[10,11]

Adult circle absorber systems. The humidity of gases inhaled by patients placed on adult circle systems depends on fresh gas inflow, ventilatory minute volume, volume of exhaled carbon dioxide, and previous use of the system.[12] A patient exhaling approximately 200 ml. of CO_2 per minute, automatically ventilated on a fresh dry circle absorber system at a minute volume of 6 L/min., with a fresh gas inflow from the anesthesia machine of 5 L/min., inhales gases with a relative humidity of 30% at room temperature. The humidity rises and stabilizes at approximately 60% after 90 minutes. Decreasing the fresh gas inflow to 500 ml./min. raises the original humidity to 48%, after which it will reach a stable 93% in 100 minutes. Previous use of the system raises the original humidity of a system receiving a fresh gas inflow of 5 L/min. to 45% without altering the period of stabilization or final humidity.

It is possible to estimate the humidity of the gases inspired by a patient placed on a circle absorber system after the period of stabilization is

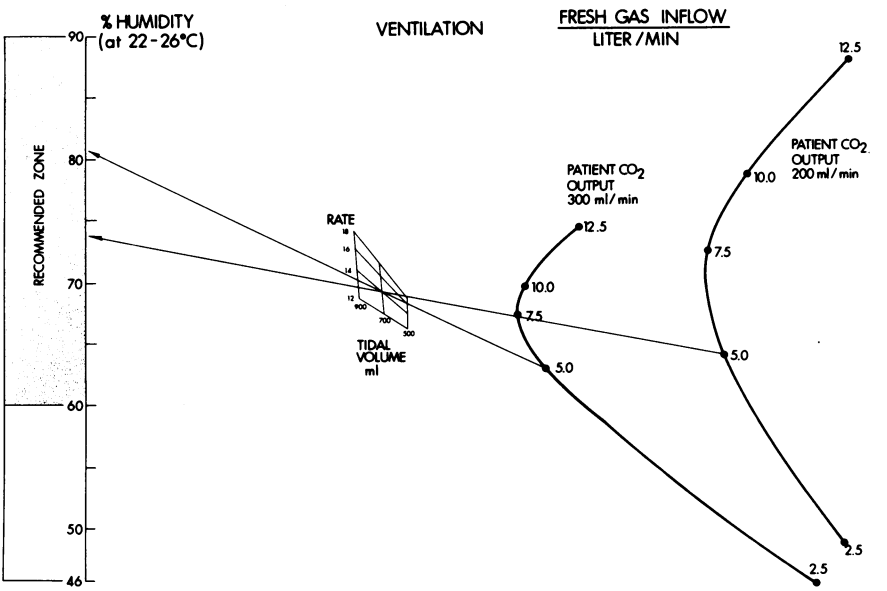

Fig. 2. Nomogram predicting the humidity output of adult circle systems in relation to VCO_2, fresh gas inflow, and respiratory rate and tidal volume. For instance, for a patient whose VCO_2 has been estimated to be in the region of 200 ml./min. (because of his height, weight, and medical history) and who has been anesthetized for at least 90 minutes on a circle system receiving a fresh gas inflow of 5 L/min., with a respiratory rate of 14/min. and a tidal volume of 700 ml., take the FGI point of 5 L/min. on the curve at the extreme right (VCO_2 = 200 ml./min.), join this to the intersection of the respiratory frequency line of 14 and tidal volume line of 700 on the grid in the center of the figure and extend until intersection with the humidity line on the left. In this instance one reads 74%. Reproduced by permission from Chalon, J., Kao, Z. L., Dolorico, V. N., and Atkin, D. H.: Humidity output of the circle absorber system. *Anesthesiology 38:*458-65, 1973, Figure 5.

completed if the amount of carbon dioxide he exhales is estimated according to height, weight, and medical history at known ventilatory minute volumes and fresh gas inflow. A nomogram has been constructed to predict this humidity.[12] For example, for patients exhaling between 200 and 300 ml. CO_2/min., the nomogram illustrated in Figure 2 permits estimation of the moisture content of inhaled gases. Another nomogram can be consulted[12] to estimate the moisture content of gases inhaled by patients with a CO_2 output of 100 ml./min. If these patients are placed on adult circle systems with a fresh gas inflow of 5 L/min. and ventilated at a minute volume of 4 L/min., they inspire gases with a relative humidity

of only 47%. To increase the humidity to just over 60% it is necessary to reduce the fresh gas inflow to 2.5 L/min.

Bloomquist infant circle. The humidity of the Bloomquist infant circle falls far below minimum recommended standards.[14] Only a child with a VCO_2 of 60 L/min. (i.e., weighing around 20 kg.) can generate enough moisture through the reaction of neutralization of the lime, and this only when the fresh gas inflow is reduced to 1 L/min. As suggested by Berry and Hughes-Davies,[15] humidity can be increased considerably by reversing the ventilator or bag attachment and the fresh gas inflow connection. With this reversed flow pattern, inspired moisture varies from 5 to 25 mg. H_2O/L (50 to 100% relative humidity at room temperature). Nomograms are available[14] to predict inspired humidity for most commonly used respiratory settings.

Columbia pediatric circle. The humidity produced by the Columbia pediatric circle (3 to 20 mg. H_2O/L) is greater than that of the unmodified Bloomquist infant circle (1-11 mg. H_2O/L) at equal fresh gas inflow rates and VCO_2.[16] At a fresh gas inflow of 1 L/min. all humidity values after a two hour period of stabilization are above the safe level as long as the VCO_2 attains or exceeds 30 ml./min. A nomogram is available to predict the humidity output of the system for most commonly used respiratory settings.[16]

Adult Tube Bag Systems

Semiclosed tube bag systems (Mapleson A and nonrebreathing systems) are almost always used with a high fresh gas inflow (two to three times the minute volume of the patient) to prevent rebreathing of carbon dioxide. This clears the circuit of most of the water vapor exhaled by the patient except for that which condenses in the mechanical dead space. The humidity of gases delivered by these systems is, therefore, low, and can be improved by inserting vaporizers, nebulizers, or heat and moisture exchangers in the circuitry.

Heat and moisture exchangers. A Garthur heat and moisture exchanger will adequately humidify a nonbreathing system.[17] An inhaled humidity of 55% at room temperature will be obtained 15 minutes after the onset of anesthesia which will reach and stabilize itself at 62% (one degree Celsius above room temperature) within one hour. The cost of the higher flow rates necessary to operate these systems is offset by the low cost of

equipment sterilization and by elimination of expensive disposable breathing tubes used with increasing frequency with circle systems.

Use of nebulizer to humidify nonrebreathing systems. Nebulizers deliver water droplets which may contain solutes or particles (including bacteria) in contrast to vaporizers which emit gaseous water. The number and size of droplets delivered to patients by a nebulizer placed in the anesthesia circuit depends on the characteristics, flow settings, and temperature control of the device and on its distance from the patient. The system devised by Tayyab et al.[18] is particularly safe in that respect as it restricts the weight of particulate water it delivers to between 15 and 20 mg. per liter of gas. Extreme care and attention to the sterilization of all components of circuits which incorporate nebulizers is mandatory because live bacteria are washed into the airways of patients placed on contaminated systems.

Pediatric tube bag system. The most commonly used pediatric tube bag system is the one described by Jackson Rees, who employs a modified Ayre's T-piece. It is generally used as a semi-open system with fresh gas inflows two to three times the child's minute volume. In addition to preventing rebreathing of most of the exhaled carbon dioxide, these high gas inflows also reduce the amount of moisture available to patients who breathe spontaneously. Controlling the ventilation, however, raises both inspired concentration and humidity.[19] For instance, a 10 kg. child with a VCO_2 of 30 ml./min., a tidal volume of 100 ml., and a respiratory rate of 20/min., who is placed on a Rees system receiving a fresh gas inflow of 5 L/min. inspires gases containing 0.2% carbon dioxide and with a relative humidity of 15% at room temperature (3 mg. H_2O/L). If the ventilation is controlled with the same tidal volume and respiratory rate, inspired carbon dioxide concentration will reach 1% and relative humidity 80% at room temperature (16 mg. H_2O/L). It is obvious that one cannot raise the humidity delivery of the system by controlling ventilation without simultaneously elevating the concentration of inspired carbon dioxide. Inhalation of 1% CO_2 causes only moderate elevation of the arterial carbon dioxide tension to around 47 torr. While this is, generally speaking, not dangerous, it has a special importance in relation to the control of intracranial pressure. Anesthesiologists who anesthetize children undergoing intracranial surgery delude themselves if they think that they are causing cerebral vasoconstriction when they squeeze the bag of their Rees system. In fact, this maneuver produces an effect opposite that intended. Children anesthetized on Rees systems should preferably be allowed to breathe spon-

taneously and a vaporizer inserted into the circuit to raise inspired humidity.[20]

COMMENTS AND SUGGESTIONS

It is obvious that all nonrebreathing and high flow semiclosed systems should be humidified if anesthesia is expected to last over one hour.[3] Circle systems, except for the conventional Bloomquist infant circle, are usually sufficiently humidified by the reaction of neutralization of soda lime by carbon dioxide if the ventilatory minute volume and fresh gas inflow are judiciously regulated and if the VCO_2 exceeds 30 ml./min. Although circle systems do not incorporate electrically heated vaporizers, certain modifications have been suggested which will considerably elevate their humidity output. A vaporizer placed into the lime canister of an adult circle system[21] and heated by the exothermic reaction of neutralization of the lime generates an original inspired humidity of 15 ± 2 mg. H_2O/L, reaching 17 ± 2 mg. H_2O/L. within one hour and stabilizing at 21 ± 2 mg. H_2O/L after 3 hours of use with a fresh gas inflow of 5 L/min., CO_2 outputs of 100 to 300 ml./min., and a respiratory minute volume of 6 L/min. Another method to raise the inspired humidity delivered by circle systems introduces the inspiratory limb into a slightly enlarged expiratory limb[22] (cross sectional diameters respectively 2 and 3 cm.). Warm gases exhaled by the patient raise the temperature of those inhaled by 3° to 4°C. This added warmth enhances vaporization of the water droplets normally deposited in the inspiratory limb as a result of the nebulization of water condensed on the undersurface of the leaflet of the inspiratory dome valve during positive positive pressure mechanical ventilation. This causes inspired humidity to rise to more than 20% of values normally attained through the use of conventional circle systems.

We believe that humidity control in anesthesia circuitry will become mandatory in years to come, both to preserve mucosal surfaces and to regulate body temperature. It also appears likely that future efficient equipment will possess feedback systems capable both of measuring and varying inspired humidity in response to the need of the patient.

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